AM AND FM MODULATION OF A HELIUM-NEON LASER BEAM USING ACOUSTO-OPTICAL INTERACTION

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THESIS

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by

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December 1972

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by

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Lieutenant Junior Grade, Turkish Navy
B. S., Naval Postgraduate School, 1972

Submitted in partial fulfillment of the
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MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

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ABSTRACT

Acoustical amplitude and frequency modulation techniques of a CW helium-neon laser beam are presented. The communication possibilities of this beam for both cases (AM and FM) are verified. Theories are discussed for the acoustooptical modulator and the p-i-n silicon photodetector. Designs of the elements of the systems and experimental results are presented. Operation of both systems is discussed.

TABLE OF CONTENTS

I. INTRODUCTION ---------- 5

- A. OBJECTIVE ---------- 5
- B. BACKGROUND ---------- 5

II. THEORY OF ACOUSTOOPTICAL MODULATION ---------- 7

III. SYSTEMS UNDER INVESTIGATION ---------- 14

- A. AMPLITUDE MODULATED ACOUSTICAL LASER COMMUNICATION SYSTEM- 14
  - 1. TRANSMITTER ---------- 14
  - 2. DETECTOR ---------- 16
  - 3. DETECTOR PRE-AMPLIFIER ---------- 21
  - 4. DETECTION PROCESS ---------- 23
  - 5. EXPERIMENTS ---------- 25
- B. FREQUENCY MODULATED ACOUSTICAL LASER COMMUNICATION SYSTEM- 27
  - 1. TRANSMITTER ---------- 27
  - 2. DETECTOR AND DETECTOR PRE-AMPLIFIER ---------- 35
  - 3. DETECTION PROCESS---------- 35
  - 4. EXPERIMENT ---------- 39

IV. CONCLUSIONS ---------- 47

LIST OF REFERENCES ---------- 48

INITIAL DISTRIBUTION LIST ---------- 49

FORM DD 1473 ---------- 50

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I. INTRODUCTION

A. OBJECTIVE

It was intended to study techniques of acoustooptical modulation of a helium-neon (6328Å) laser beam. It was also decided to investigate the communication possibilities of this laser beam by means of intensity and frequency modulation. The detection and demodulation of this modulated light beam was another part of this investigation.

B. BACKGROUND

The first working laser was invented in 1960. The properties of light produced by a laser attracted many engineers and scientist toward it. These properties are: high intensity, time and spatial coherence, directionality, and the high frequency operation. It is these properties which are common to most laser applications and which permit modes of operation that in many cases had never been possible before.

The primary characteristic of laser source which is most important in optical communication is coherence. This coherence phenomenon permits very efficient modulation and detection providing the very basis for all laser communication techniques. The potentially usable bandwidth has been increased significantly in communication systems because lasers can operate in the visible and infrared region of the electromagnetic frequency spectrum, considerably higher in frequency than competitive techniques such as microwaves or radio waves. The communications capacity can be increased through the directionality of the laser beams. Electromagnetic waves at lower frequencies propagate in all directions which requires that broadcasting points must be widely separated physically in order not to

interfere with one another. The directionality properties of a laser beam permit their use close to one another with only a very little interference caused by scattering due to atmospheric particles. The laser beam has also a very narrow beamwidth, implying that power can be efficiently transmitted to distant points [Ref. 1].

These unique properties of the laser induced many engineers to develop many different types of lasers. First, gas and solid-state lasers were developed. In mid-1962, lasing action in certain semiconductor diodes was achieved.

Many optical communication experiments have been performed employing CW (Continuous Wave) operation of gas lasers in the visible region. In an experiment performed by the Bell Telephone Laboratories, baseband information frequency-modulated (FM) a 70-MHz sub-carrier signal which in turn modulated the optical beam by means of an acoustical modulator [Ref. 2]. A helium-neon laser was used as a signal source. Television pictures and voice frequency-multiplexed signals were transmitted over a one-mile path. Both amplitude and phase modulation of the optical carrier was employed with direct and heterodyne receivers.

Other optical communication experiments using a laser television display were performed by the Zenith Radio Corporation [Ref. 3]. In this experiment light from a helium-neon laser was frequency-modulated by the ultrasonic waves produced by the Brag diffraction modulator. The modulator was driven by the frequency-modulated video power and water was used as the interaction medium.

II. THEORY OF ACOUSTOOPTICAL MODULATION

The modulation of a light wave is controlled variation of some property of the wave such as its amplitude, phase, frequency, polarization or direction of propagation. The major problem of laser communication is in the modulation techniques. Primarily it is to fill the enormous available bandwidth with usable signals imposed on the carrier frequency.

Light modulation can be achieved by several techniques including interferometric effects, electro-optic effects, and ultransonic diffraction cells. Most optical modulators are dependent on a variation of optical index of refraction under the control of the modulating signal [Ref. 4]. The index variation may be caused by

a. the electro-optic effect,

b. the magneto-optic effect,

c. acoustic (pressure) effects,

d. variation in charge carrier concentration in a semiconductor, or

e. combinations of these effects.

In the investigation the modulation of laser beam was studied on the basis of acoustic effects and the Bragg diffraction principles. It is well known that under the correct circumstances an optical beam passing through a transparent material containing a travelling acoustic wave has part of its energy diffracted by the refractive index variations associated with the acoustic wave [Ref. 5]. This condition is known as the Bragg diffraction phenomenon. By considering the interaction of plane wave of sound with a plane wave of light the concept of the Bragg

diffraction can easily be understood [Ref. 6]. Because of interference effects, when a plane wave of light intersects with a plane wave of sound it can be shown that the diffracted light wave will have significant amplitude only if the plane waves meet at the proper angle. The condition for diffraction may be written from the wave vector relation among the waves as

$$\vec{k\pm} = \vec{k} \pm \vec{K} \qquad (1)$$

where k and k+ are the propagation constants of the incident and diffracted light, respectively, and K is the propagation constant of the sound wave. The sign depends on the propagation direction of the sound beam. These propagation constants are defined as:

$k = \omega/c$, $k\pm = k\,(1 \pm \Omega/\omega)$, and $K = \Omega/v$, in which

ω = the optical angular frequency

c = the unperturbed light velocity in the medium

Ω = the acoustic plane wave frequency

v = the acoustic velocity

As seen from Eq. (1) the propagation vectors of incident light and sound yield the vector of diffracted light. This wave vector relation can be constructed as shown in Fig. 1.

Typical sound frequencies used for communication purposes are very much less than the light frequencies, therefore

$$|\vec{k\pm}| \approx |\vec{k}| \qquad (2)$$

then from Fig. 1, the angle θ_B can be defined:

$$\text{Sin}\ \theta_B = \frac{|K/2|}{|k|} = \frac{\lambda}{2\Lambda} \qquad (3)$$

where Λ is the wavelength of the sound wave, λ is the wavelength of the light in the diffracting medium, and θ_B is the Bragg angle.

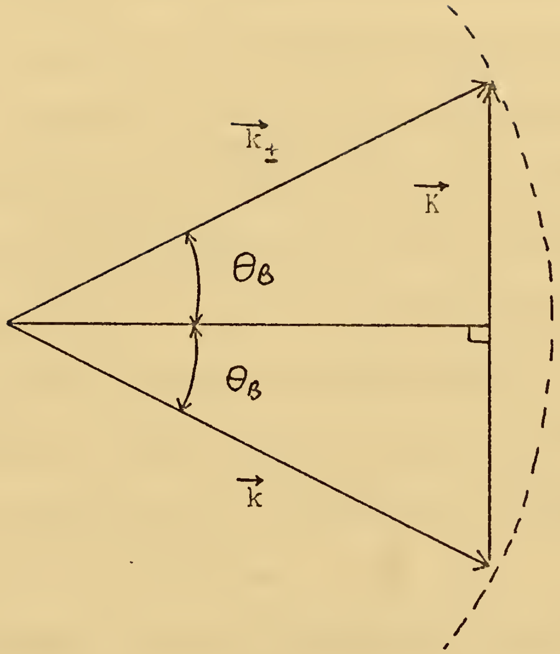


FIGURE 1 : THE WAVE VECTOR RELATION BETWEEN LIGHT AND ACOUSTIC WAVES FOR DIFFRACTION (AFTER REF. 9) (If the direction of $\vec{k}$ and $\vec{K}$ is changed, the vector sum ($\vec{k}$ + $\vec{K}$) no longer falls on the circle and no diffraction can occur.)

The frequency relations between the incident and the diffracted waves can be derived from the parametric interaction theory [Ref. 7]

$$\omega_\pm = \omega \pm \Omega \qquad (4)$$

where $\omega_+ = \omega + \Omega$ and $\omega_- = \omega - \Omega$ are respectively called the up-shifted and the down-shifted first order diffracted beam frequencies. (The $\pm$ relates the frequency of the diffracted wave to the respective sign in the vector equation.) The zero-order diffracted beam has the same frequency as the incident light beam. These diffracted frequency values depend on whether the incident light wave is directed into the progressing sound wave or behind it. An up-shifted firstorder diffracted beam is produced in the first case and down-shifted in the second case, as shown in Fig. 2. The frequency change is equivalent to a doppler shift. This relation will be used later in frequency modulation of the laser beam with the sound beam.

Light modulation can be accomplished by sound waves which are produced in the acoustic modulator when the geometrical conditions for Bragg diffraction are properly met. The sound wave can modulate the light in amplitude and phase, deflect it, focus it, or shift its frequency [Ref. 8]. The amplitudes of the diffracted waves are proportional to the product of the amplitudes of the incident light and sound plane waves

$$U_\pm \; \alpha \; U_\ell \cdot U_S \qquad (5)$$

where $U_\pm$ are the diffracted waves, U_ℓ is the incident light wave and U_S is the sound wave amplitude. The proportionality constant is a function of the interaction medium and the ratio of the acoustic wavelength to the light wavelength (Λ/λ). The phase of the diffracted wave is depended on whether the wave is up-shifted or down-shifted in frequency

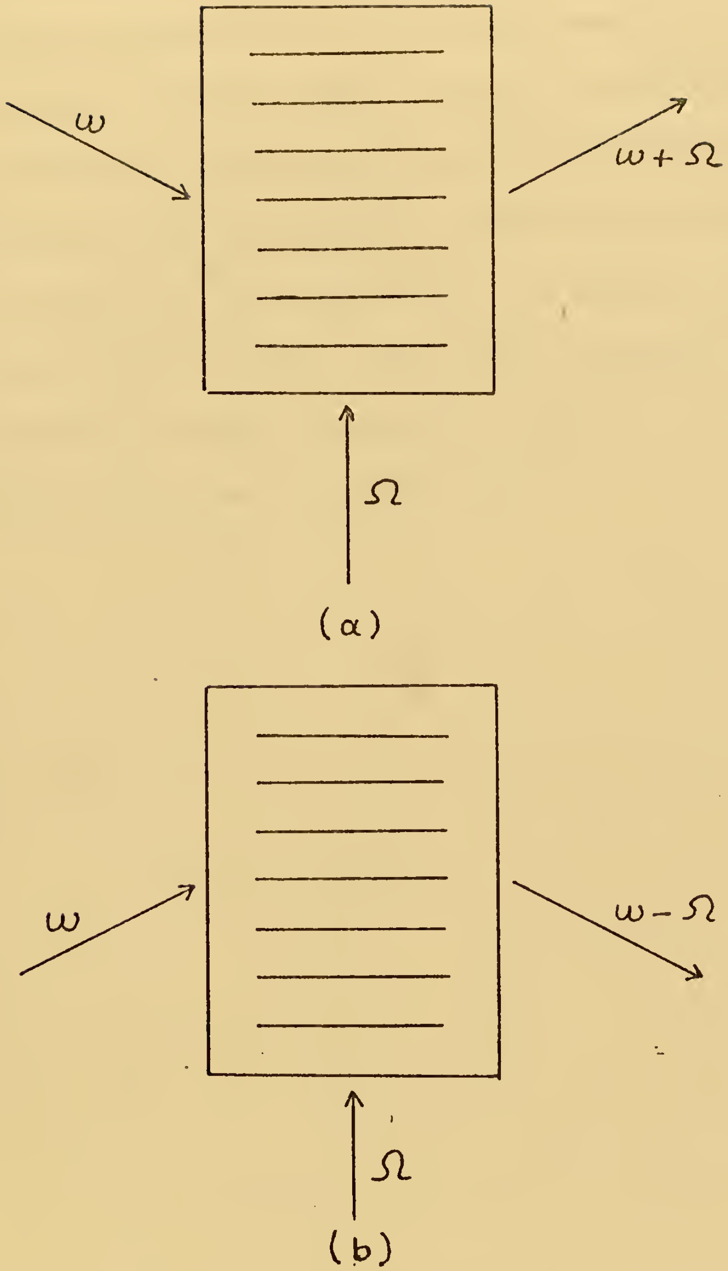


FIGURE 2: BRAGG REFLECTION (a) Up-shifted Diffracted Beam

(b) Down-shifted Diffracted Beam

(Up-shifted or down-shifted beam is selected by making light and sound meet under the appropriate angle) . (AFTER REF. 8)

[Ref. 6]. In the first case the sum of the phases of the light and sound plane wave is produced, and in the second case the difference. The typical Bragg diffraction acoustooptical modulator is shown in Fig. 3. The amplitude modulation of the sound beam causes a corresponding intensity modulation (IM) on each of the diffracted beams at the acoustic frequency. The frequency modulation of the sound wave result in frequency modulation of each of the diffracted beams from the acoustic modulator as seen in Eq. (4). The frequency shift of the diffracted beam is exactly equal to the acoustic frequency. Only one of the three diffracted beams is useful for purposes of communication; the others may be eliminated by a field stop.

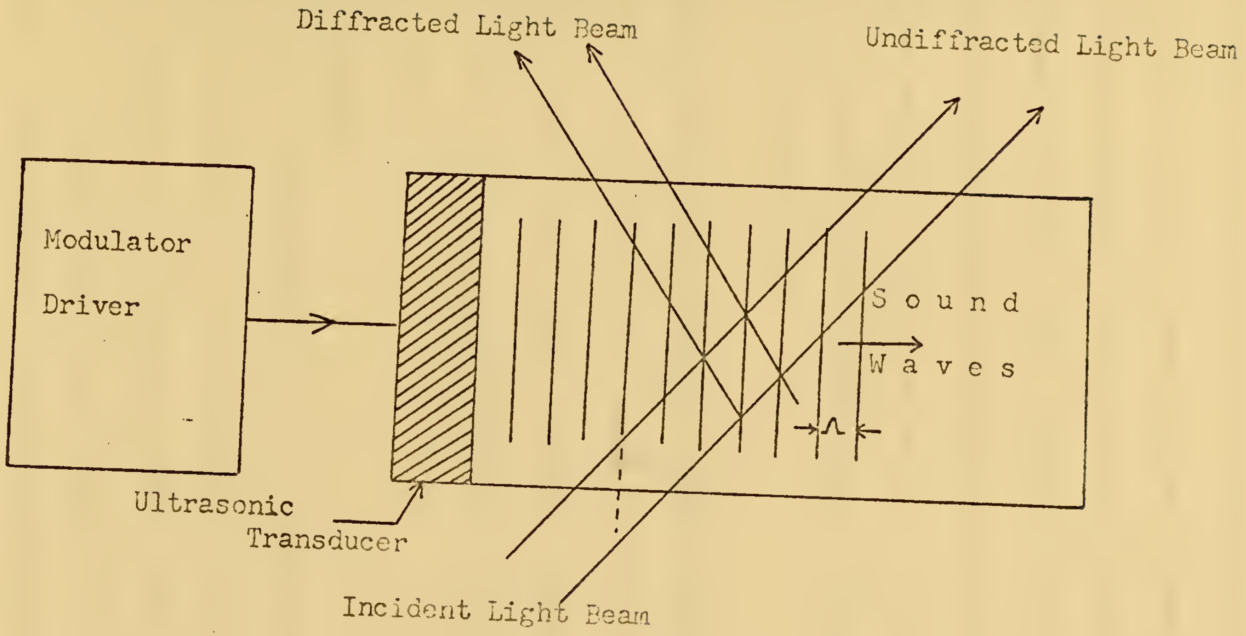


FIGURE 3 : BRAGG ANGLE ACOUSTOOPTIC MODULATOR

III. SYSTEM UNDER INVESTIGATION

The optical communication application of the laser beam was studied by using amplitude modulation and frequency modulation techniques of that beam. In general optical communication systems can be broken down into five parts corresponding to parts of radio and other electrical communication systems [Ref. 9]. These components are: an oscillator to generate the carrier wave, a modulator to impress information on the wave, a transmission medium to convey the wave, a device to receive the wave and convert it to an electrical signal, and a demodulator to extract the information from the wave.

A. AMPLITUDE MODULATED ACOUSTICAL LASER COMMUNICATION SYSTEM

For this experiment a helium-neon laser operating at 6328 Å was to be employed as the light signal source. A typical amplitude modulated acoustical laser communication system block diagram can be constructed as shown in Fig. 4.

1. Transmitter

Signal transmission was to be accomplished by amplitude modulation of the laser beam in the acoustical modulator medium at a sub-carrier frequency in the megahertz (MHz) range. The acoustical wave is generated by a high-frequency signal generator driving an acoustical transducer. This acoustical wave generator can be externally amplitude modulated (AM) with an information signal of different wave forms, such as sine wave, square wave, and triangular wave in the audio frequency range or higher. The amplitude modulated radio frequency (RF) signal is then applied to a power amplifier to get the necessary power for driving the acoustical modulator. Amplitude modulation by the RF sub-carrier

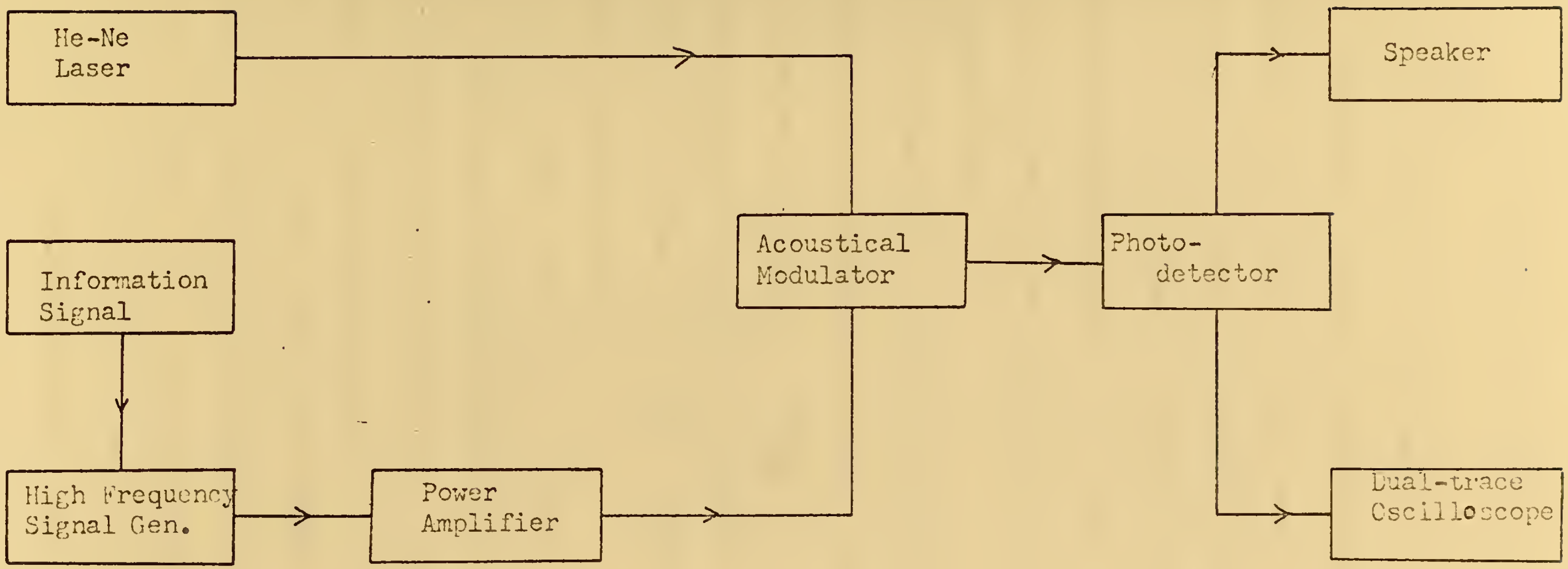


FIGURE 4 : AMPLITUDE MODULATED ACOUSTICAL LASER COMMUNICATION SYSTEM BLOCK DIAGRAM

(amplitude modulated) of the laser beam is achieved as explained in section II. The transmitter block diagram is shown in Fig. 5.

2. Detector

The light detector is a key element in an optical communications system. The optical detectors in a laser communication system convert the intensity of the optical carrier into an electrical signal. When the laser beam is intensity or frequency modulated by the acoustical modulator, the beam transmitted from the modulator is collected and focused on an optical detector. For laser communication purposes solid-state photodiodes are very useful as detectors because of their fast response time.

At the present time a variety of different types of solid-state photodetectors are available. Of these, the silicon PIN photodiode has the broadest applicability [Ref. 10]. The main advantages of the PIN photodiodes are broad spectral response, a wide dynamic range, high speed, and extremely low noise. Typical construction of a PIN photodiode is shown in Fig. 6.

A PIN photodiode consists of a reverse biased semiconductor diode. Absorbtion of incident light in or near the semiconductor junction produces hole-electron pairs. When a large reverse-bias is applied to the photodiode these hole-electron pairs (photo-generated carriers) will be swept out of the I-region, with the resulting current containing a-c components corresponding to the modulation of the incident light beam [Ref. 11]. The active region is where the high-bias field exist, between or nearly between the N and P areas (I-region). It is desirable to have the I-layer as thick as possible and P-layer as thin as possible for the highest quantum conversion efficiency

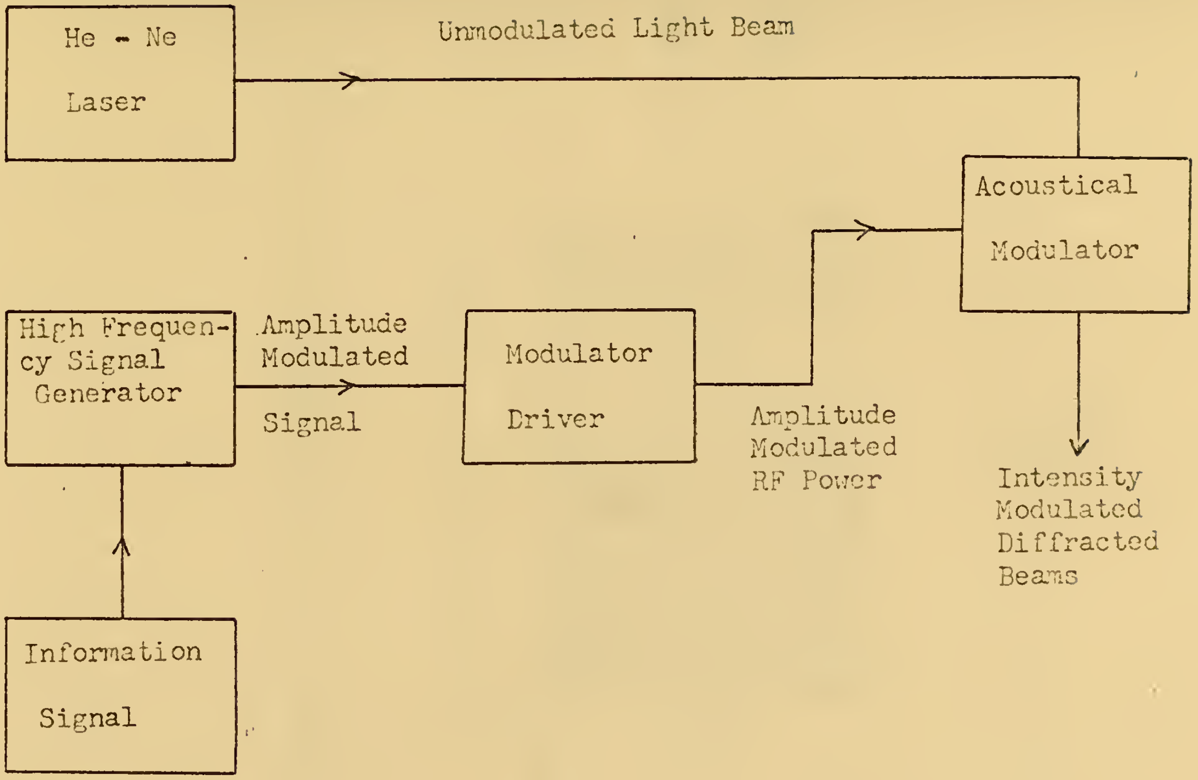

He - Ne
Laser
Unmodulated Light Beam
Acoustical
Modulator
High Frequency Signal Generator
Amplitude Modulated Signal
Modulator
Driver
Amplitude Modulated RF Power
Intensity Modulated Diffracted Beams
Information
Signal

FIGURE 5 : AMPLITUDE MODULATED ACOUSTICAL LASER COMMUNICATION TRANSMITTER

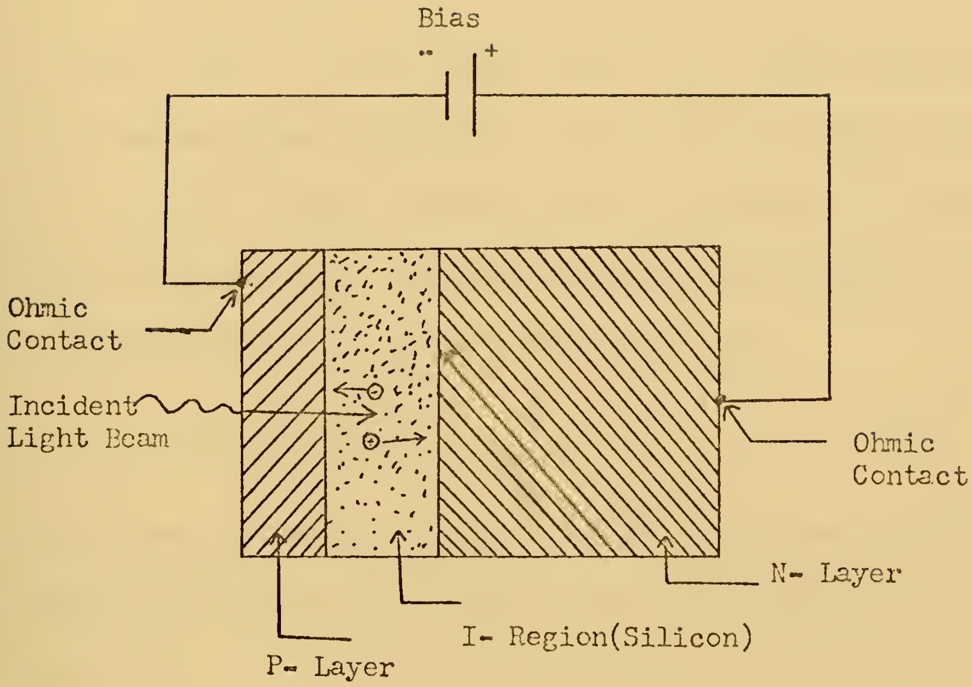


FIGURE 6 : THE CONSTRUCTION OF P-I-N PHOTODIODE

(electrons per Photon). The equivalent circuit of the PIN photodiode is as shown in Fig. 7. R_S is the series resistance which has a value inversely proportional to the thickness of the P-layer. R_p and C_p are the diode resistance and capacitance respectively. R_p has a value bigger than several gigaohms; and C_p has a value between two to five picofarads. In the presence of a signal, C_p is modulated by the conductivity of the I-layer. At high light levels, the I-layer may be saturated and C_p may become quite significant. Thus because of these effects, increase in the rise time of the detector and decrease in quantum efficiency can occur. The frequency response of the diodes to modulation are calculated from R_S and C_p according to Eq. (6).

$$\omega_c = \frac{(1 + R_S/R_p)}{R_S\ Cp} \simeq \frac{1}{R_S\ Cp} \qquad (6)$$

where ω_c is the 3-dB cutoff frequency and the approximation depends on the assumption that $R_S/R_p \ll 1$. The current resulting from the incident illumination is i_p, i_N is the noise current of the device and i_R is the dark current which has a value determined by the construction and the dimension of the particular diode type.

The thickness of the I-layer is proportional to the magnitude of the electric field applied to the diode. When the reverse bias voltage is increased from zero volts, three beneficial events occur: hole-electron transit time decreases, conversion efficiency (electrons per photon) increases slightly, and the junction capacitance decreases.

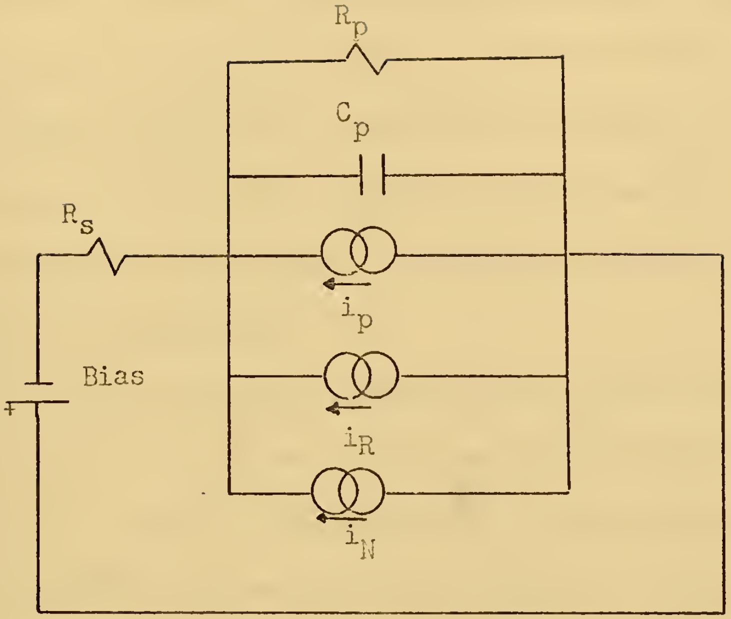


FIGURE 7 :PHOTODIODE EQUIVALENT CIRCUIT (AFTER REF.10)

3. Detector Pre-Amplifier

The current level produced by the photodiode is proportional to the input light power. When dealing with low-level signals, an amplifier is required to get a usable signal level. The speed of response of the PIN diode is limited by the terminating pre-amplifier. Reverse bias applied by the amplifier circuit to the photodiode should be as high as possible (up to 50 volts) in order to reduce the diode shunt capacitance C_p and slightly enhance the sensitivity (microamperes per microwatt). The input resistance of the amplifier must be as high as possible to satisfy high gain or low noise requirements, but as low as necessary for high speed of response [Ref. 12].

The typical detector pre-amplifier circuit used in this work is shown in Fig. 8. In general the transistor T2 should have low Cob as well as low Cie, and its gain-bandwidth product should be at least fifty times the highest desired operating frequency. The transistor T1 is connected as an emitter follower for impedance matching to the photodiode and its emitter is connected to the base of T2. Negative feedback is obtained by connecting the resistance R_f from collector of T2 to the base of T1. The use of negative feedback enables a combination of low-noise properties and high-speed operation. The signal voltage at the collector of T2 is the product of the feedback resistance R_f times the photodiode current (signal current). The bias can be obtained for T1 from either the photodiode or from the feedback resistor. Bias for T2 is obtained by connecting a high enough value of resistance between its base and ground so that all of the emitter current of T1 does not pass to ground.

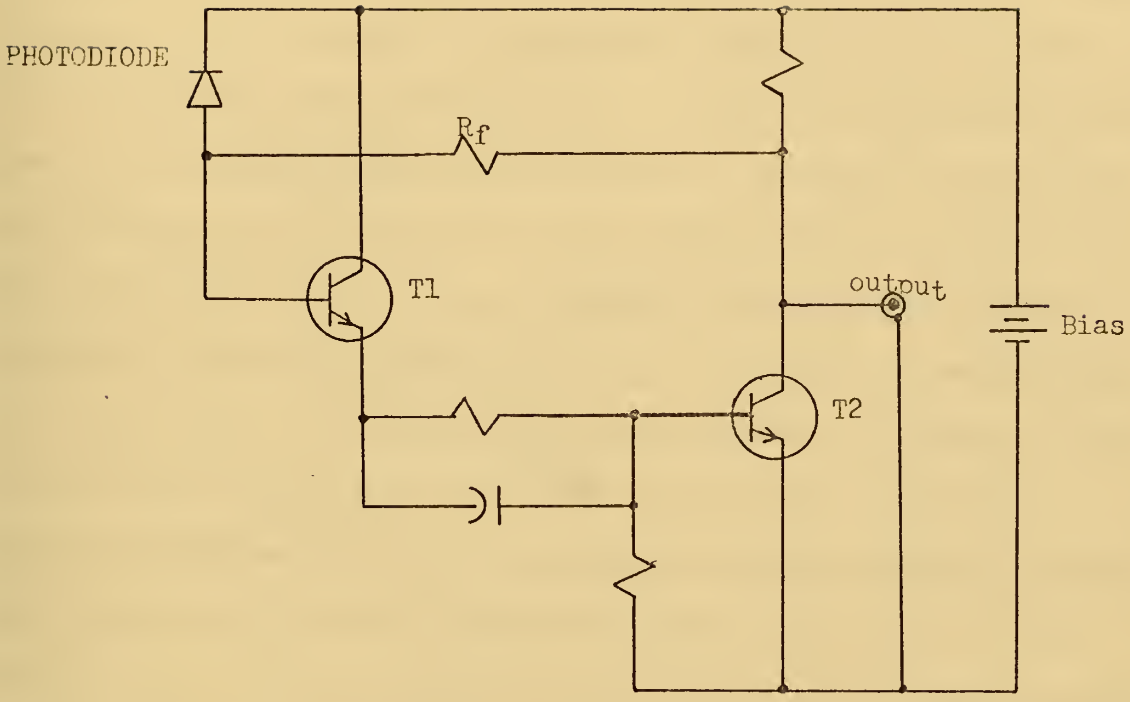


FIGURE 8 :DETECTOR PRE-AMPLIFIER (AFTER REF.12)

4. Detection Process

The principle in an optical communication system is the same as in radio which transmits information by modulating the amplitude, phase, or frequency of a carrier and transmits the modulated carrier to a receiver where the signal represented by the modulation is demodulated by a detection process. The detection process can be accomplished by using direct photodetection or a heterodyne photodetection technique.

The direct detection technique is useful for amplitude modulated (AM) or the intensity modulated (IM)signals. The operation of any AM photodetector can be divided into two processes: first, the conversion of light into photo-current whose ac component represents the detected modulation, and second, conversion of the ac component of photo-current into output power. The current generating process is a perfect "square-law" process in which the output current is directly proportional to the input power and hence to the square of the input amplitude. Therefore the result is a direct demodulated signal at the output of the photodetector. In this process the photodetector has no special arrival angle requirement for detection except that the photons be intercepted by its photo-sensitive area.

A typical direct detection set-up for the diffracted light from the acoustical modulator, which is intensity modulated (IM) with the envelope of the modulation sub-carrier, is shown in Fig. 9. One of the first order (up-shifted or down-shifted) diffracted beams out of the acoustic modulator can be selected by an adjustable iris to fall on the photodetector. Intensity modulation on these beams produces ac voltage at the photodetector output. The modulated and the demodulated signals can be displayed on a dual trace oscilloscope.

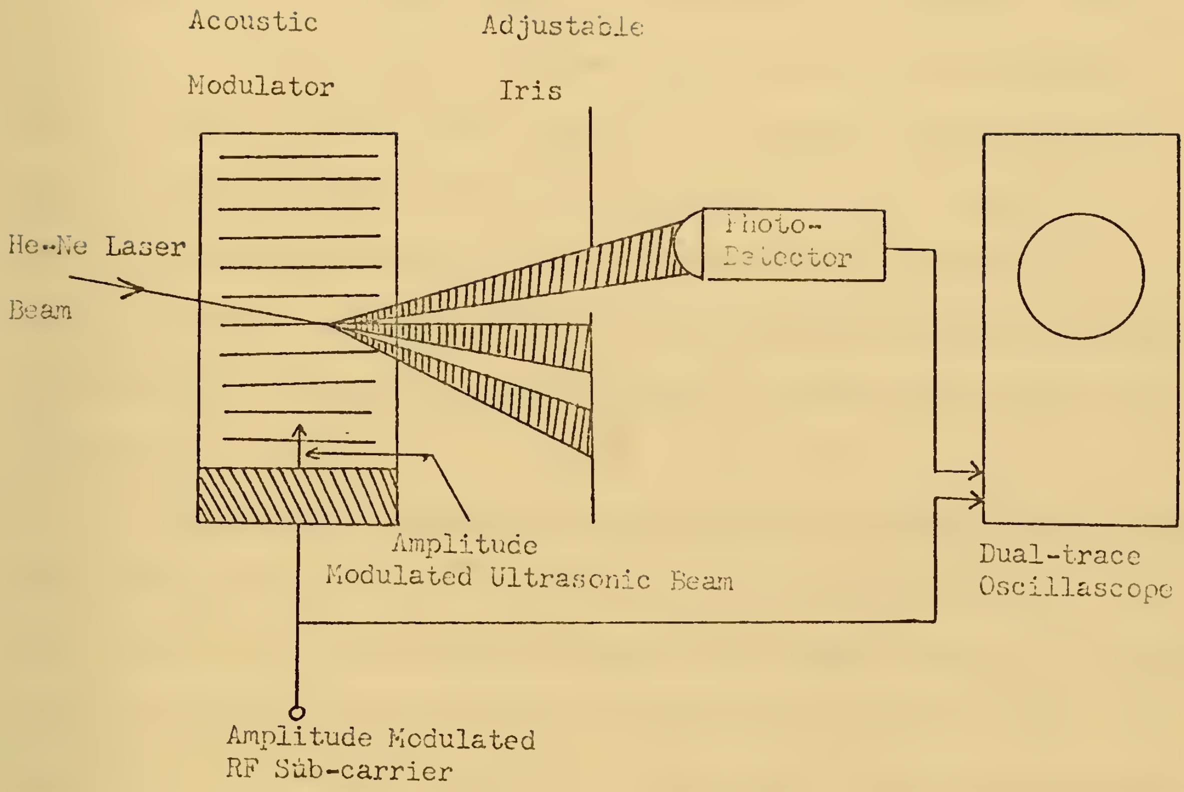


FIGURE 9 : DIRECT DETECTION SET-UP FOR INTENSITY MODULATED DIFFRACTED LIGHT BEAM

5. Experiment

For this experiment the light source was a helium-neon laser (1.5 mW output power). The amplitude-modulated 15-MHz rf sub-carrier signal was obtained by external amplitude modulation of the high-frequency signal generator with the information signal provided by an audio oscillator. This 15-MHz rf sub-carrier frequency was used because it was one of the resonant modes of the acoustical modulator. This signal was fed to the wide-band power amplifier to get the necessary driving power for the acoustic modulator. Distilled water was used as the interaction medium in the acoustic modulator and the amplitude modulated sound beam was produced by a quartz-crystal transducer of 1-MHz fundamental frequency excited with the amplitude modulated 15-MHz (15th harmonic frequency of the transducer) rf sub-carrier signal from the modulator driver.

The frequency response of the ultrasonic transducer was determined by measuring the intensity of light in the first order diffracted beam as a function of rf sub-carrier frequency with input voltage at the quartz crystal terminals held constant. The normalized intensity versus frequency curve is plotted in Fig. 10. The bandwidth of the transducer is approximately 50 kHz.

The light modulation was achieved in the acoustic modulator as described in Section II. One of the first order (up-shifted) intensity modulated diffracted beam was selected by an adjustable iris from the acoustic modulator and allowed to fall on the photodetector. An HP-4220 photodiode (with a circular active area diameter of 0.020 inch) was used as a light detector.

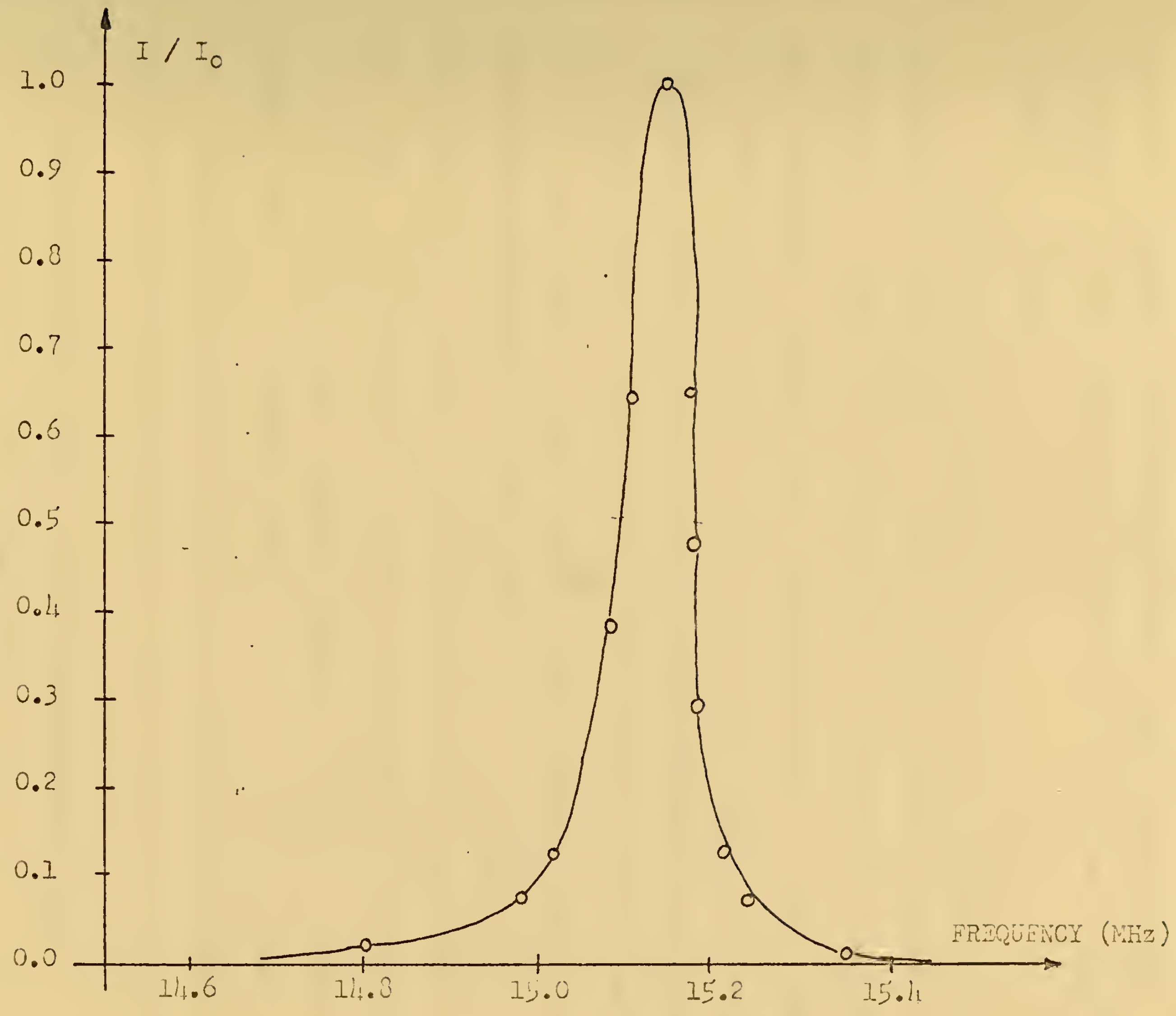


FIGURE 10 : THE FREQUENCY RESPONSE OF THE QARTZ-CRYSTAL TRANSDUCER

The detector pre-amplifier circuit was designed as described in section III-3. This circuit is as shown in Fig. 11. The demodulated signals from the detector pre-amplifier and the amplitude modulated rf sub-carrier signals from the high-frequency signal generator were displayed and photographed on the dual-trace oscilloscope as shown in Figures 12, 13, and 14.

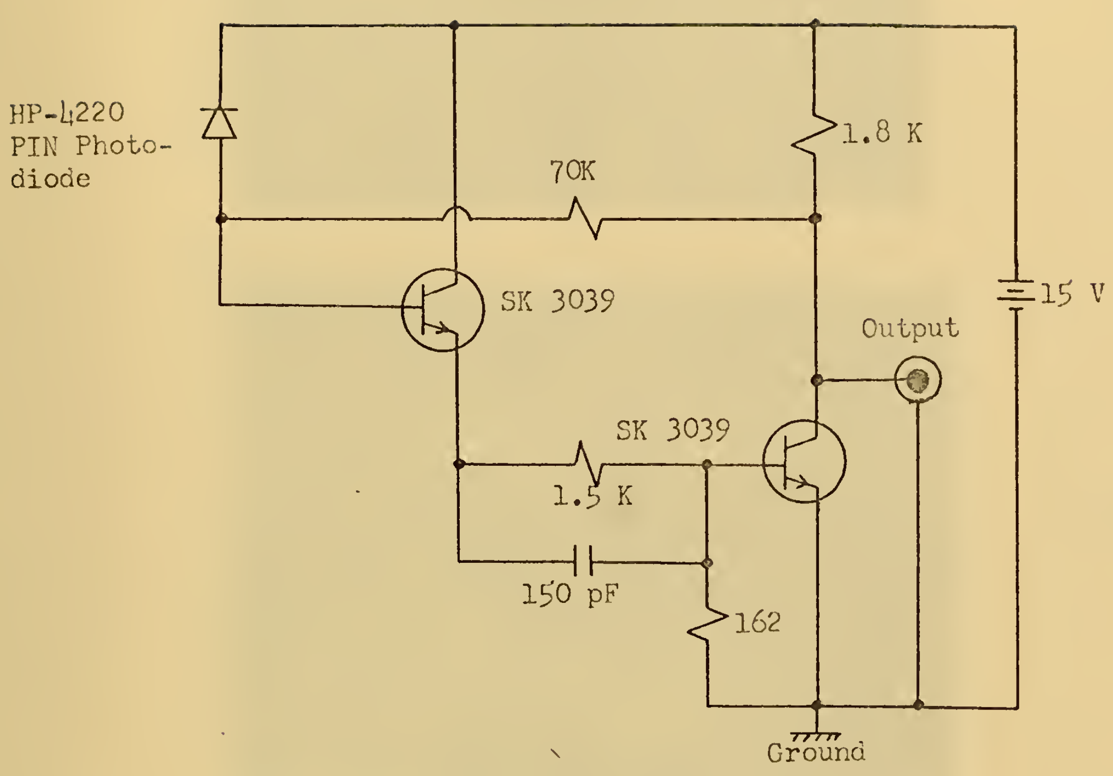
The communication possibilities of the above experiment was verified using an audio output of a radio as the information signal to modulate the 15-MHz rf sub-carrier signal. The same light modulation and demodulation scheme was used as described before. At the output of the detector pre-amplifier the demodulated signal levels were very low, therefore an audio amplifier (which has 20-kHz bandwidth) was designed as shown in Fig. 15. The demodulated output signals from the photodetector were applied to this amplifier input, then the output of the amplifier was displayed and photographed on the dual-trace oscilloscope as shown in Fig. 16, and it was also monitored with a loud speaker. At the output of the speaker the sound was intelligible, but the fidelity of the sound was not good. Possible reasons for the poor fidelity are feeding the output of the photodetector into the audio amplifier without any filtering or processing, pickup noise by the audio amplifier, and improper impedance matching between the audio amplifier and the speaker.

B. FREQUENCY-MODULATED ACOUSTICAL LASER COMMUNICATION SYSTEM

The block diagram of this system is shown in Fig. 17.

1. Transmitter

A frequency modulated rf sub-carrier signal can be provided by external frequency modulation of a high frequency voltage-controlled



* R in Ohms

FIGURE 11 : THE DETECTOR PRE-AMPLIFIER CIRCUIT

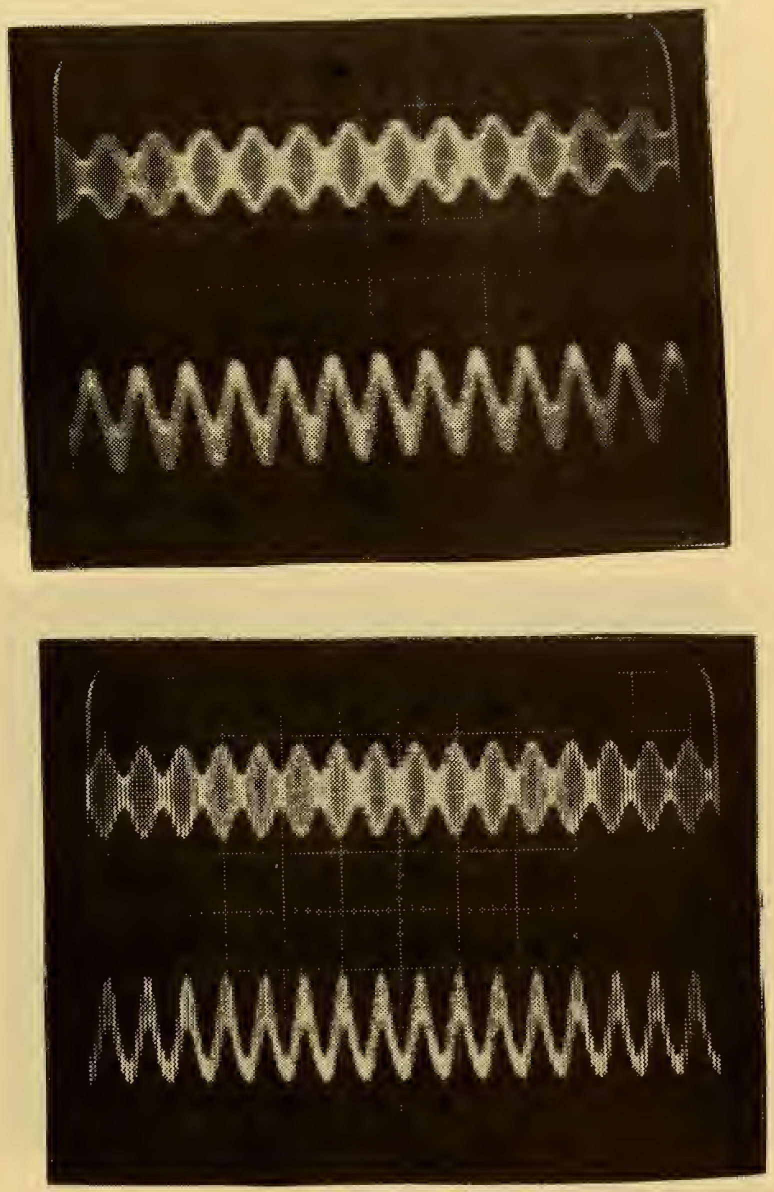


FIGURE 12 : SINE WAVE MODULATED SIGNAL (UPPER TRACE) AND DEMODULATED OUTPUT (LOWER TRACE)

(a) Modulating signal 6-kHz, (b) Modulating signal 20-kHz

(Note : The apparent chopping of the signals is due to the action of the dual trace oscilloscope)

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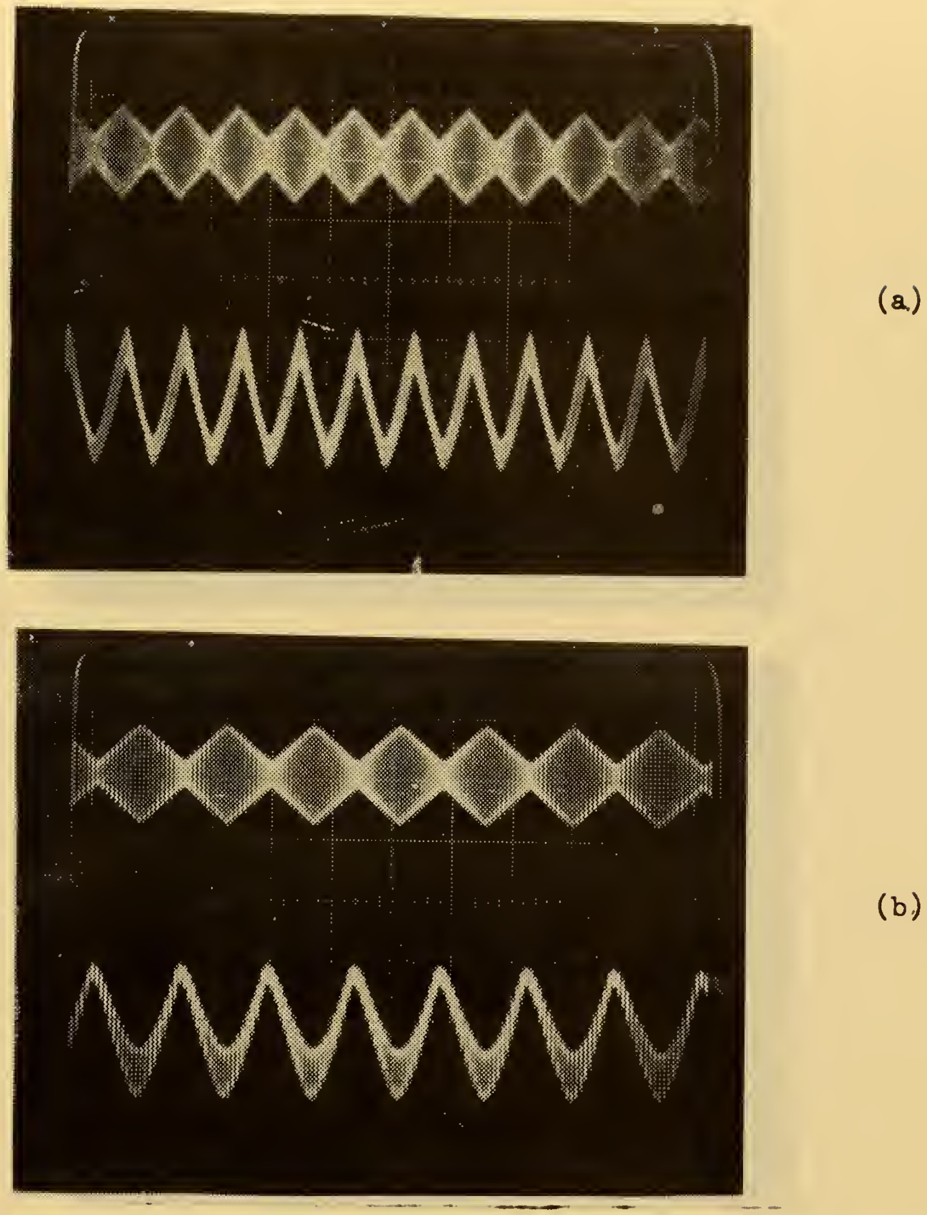

FIGURE 13 : TRIANGULAR WAVE MODULATED SIGNAL (UPPER TRACE) AND DEMODULATED OUTPUT (LOWER TRACE)

(a) Modulating signal 2-kHz, (b) Modulating signal 7-kHz

(Note : The apparent chopping of the signals is due to the action of the dual trace oscilloscope)

[illegible]

[illegible]

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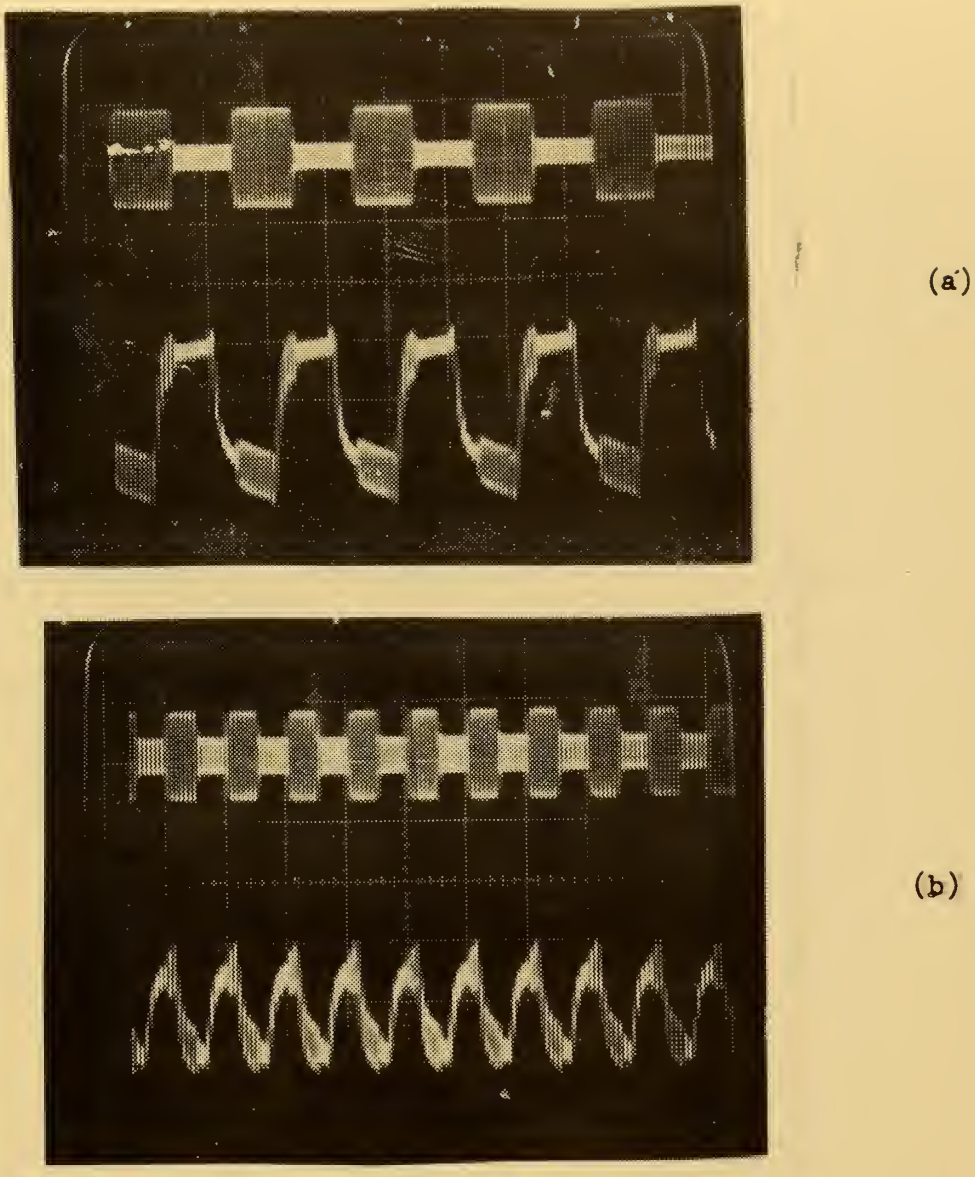

FIGURE 14 : SQUARE WAVE MODULATED SIGNAL (UPPER TRACE) AND DEMODULATED OUTPUT (LOWER TRACE)

(a) Modulating signal 5-kHz, (b) Modulating signal 10-kHz

(Note : The apparent chopping of the signals is due to the action of the dual trace oscilloscope)

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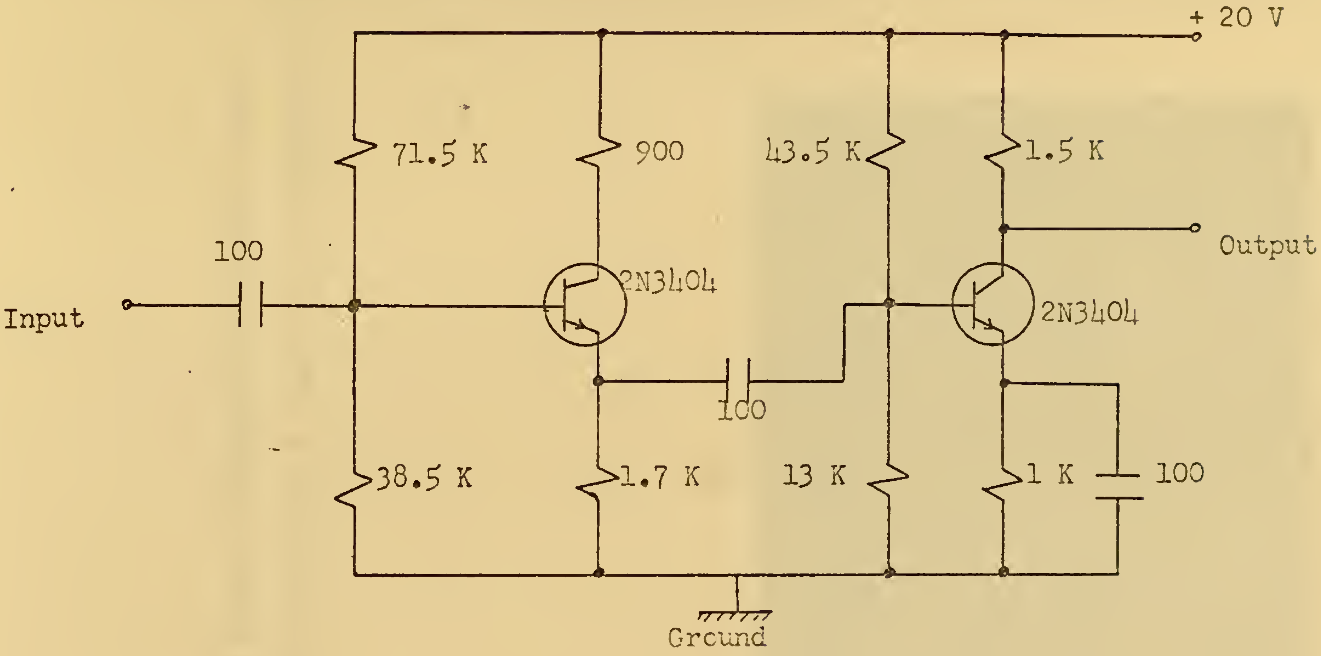


* R in Ohms

C in Microfarads

FIGURE 15 : TWO STAGE AUDIO AMPLIFIER

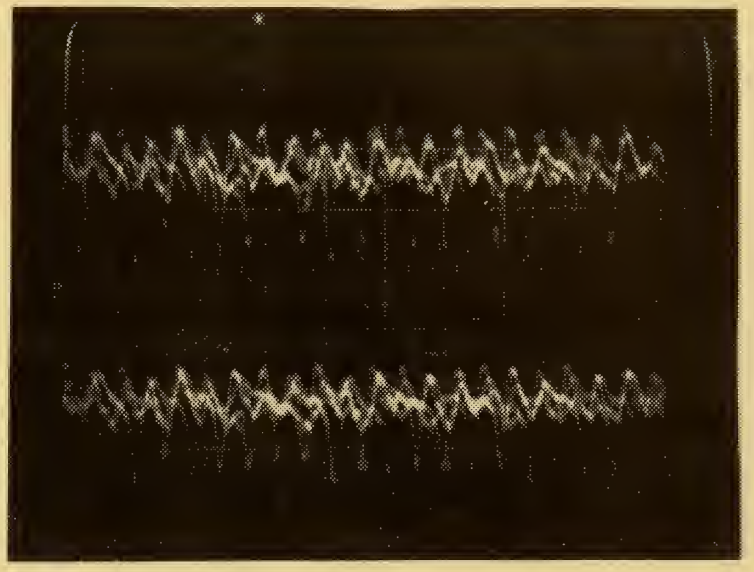
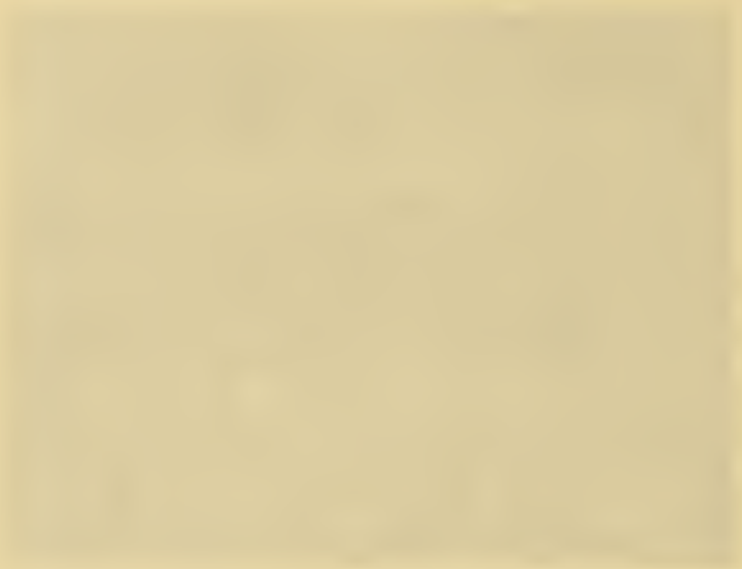


FIGURE 16 : MODULATING SIGNAL FROM A RADIO(UPPER TRACE) AND DEMODULATED OUTPUT FROM THE PHOTODETECTOR (LOWER TRACE)



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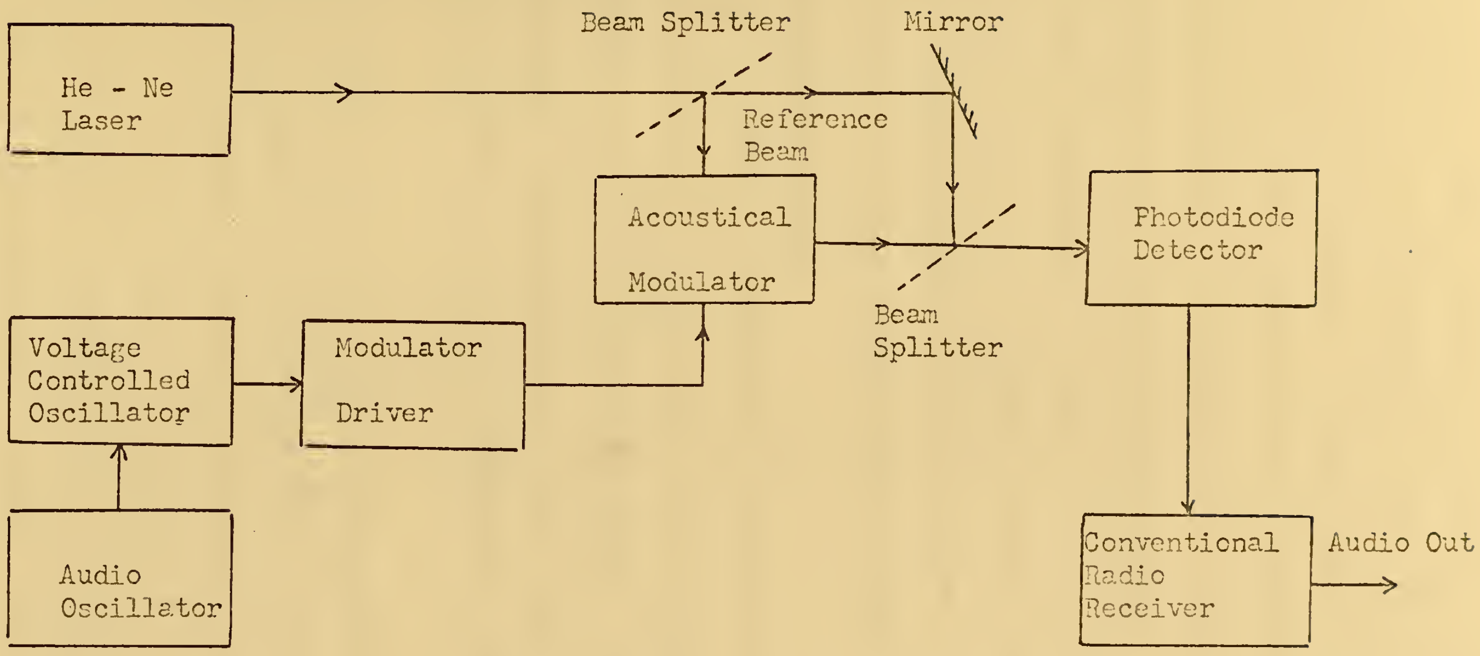


FIGURE 17 : FREQUENCY MODULATED ACOUSTICAL LASER COMMUNICATION SYSTEM

oscillator with an audio frequency oscillator. The rf sub-carrier signal is then applied to a power amplifier to get the necessary rf power to drive the acoustical modulator. Frequency modulation between the laser beam and the frequency modulated rf sub-carrier signal can be achieved in the acoustic modulator as described in Section II.

2. Detector and the Detector Pre-Amplifier

With the addition of a beam of light at the unshifted frequency the same type detector as described in Section III-A, can be used to detect the frequency-modulated diffracted beam. The detector pre-amplifier is different because of difference in signal frequency.

3. Detection Process

The heterodyne photodetection process ban be used to detect a frequency modulated diffracted beam. This arrangement provides very good discrimination against unwanted signals. Optical detectors measure intensity rather than amplitude of incident electromagnetic waves. Heterodyne detectors in optical communication system also operate in this manner.

As shown in Fig. 18, ideally, two coplanar electromagnetic light waves of different frequencies fall on the same area of a photodetector. The resultant signal on the detector is given by

$$U_t = U_1 \mathrm{Cos}\,\omega_1 t + U_2 \mathrm{Cos}\,\omega_2 t \tag{7}$$

where U_1 and U_2 are the amplitudes and ω_1 and ω_2 are the angular frequencies of the two incident waves. To detect the presence of the signal, the photo-intensity must be measured, which is given by the square of Eq. (7):

$$U_t^2 = U_1^2 \mathrm{Cos}^2 \omega_1 t + U_2^2 \mathrm{Cos}^2 \omega_2 t + U_1 U_2 \mathrm{Cos}\,(\omega_1 + \omega_2) + U_1 U_2 \mathrm{Cos}\,(\omega_1 - \omega_2) \tag{8}$$

Since ω_1 and ω_2 are in cases of current interest at optical or near infrared frequencies, the electrical detection of these terms of frequency ω_1, ω_2 and the sum $(\omega_1 + \omega_2)$ is impossible. It has been shown that the electron-photon correlation time required for the generation of electron-hole pairs in the detector is on the order of 3×10^{-12} seconds, therefore the detector can not respond to signals at these optical frequencies [Ref. 13]. Under these condition only the average of these high frequency terms can be detected by the detector. The average value of $\mathrm{Cos}^2\, \omega t$ term is one-half, and the average of $\mathrm{Cos}\,(\omega_1 + \omega_2)$ is zero. The final result for the detector output is then

$$U_t^2 = \frac{U_1^2}{2} + \frac{U_2^2}{2} + U_1 U_2 \,\mathrm{Cos}\,(\omega_1 - \omega_2)\, t \qquad (9)$$

It can be seen that from the Eq. (9) the output of the detector represent both a constant or direct current component and the difference or beat frequency. The modulation on this beat frequency is extracted by a conventional radio-frequency receiver or some electrical detector depending upon the modulation type.

By using the heterodyne photodetection ideas, discussed above, the frequency-modulated diffracted light beams from the acoustical modulator can be detected. A typical set-up for this process is shown in Fig. 19. In order to obtain two coherent beams for use in optical heterodyne mixing it has been common practice to use a beam splitter and mirror assembly similar to that shown schematically in Fig. 19. The configuration shown would be appropriate for heterodyne (coherent) detection of light modulated by Bragg diffraction from an acoustic wave. The optical configuration can be arranged, so that a portion of the original incident light falls into the same solid angle as does

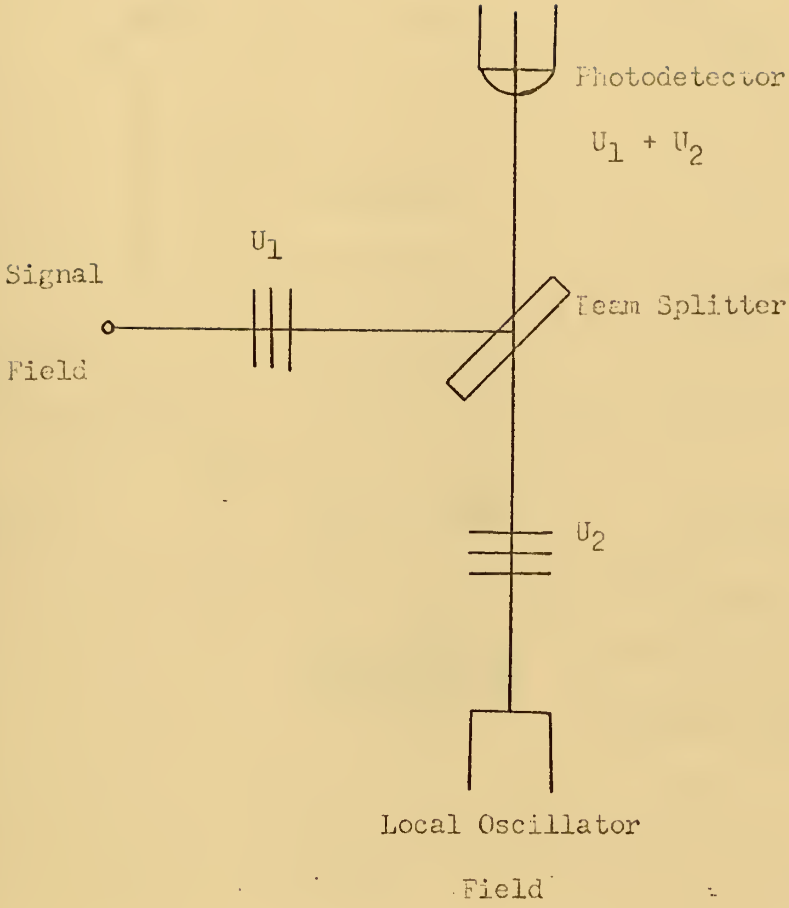


FIGURE 18 :A TYPICAL HETERODYNE DETECTION SET-UP (AFTER REF. 14)

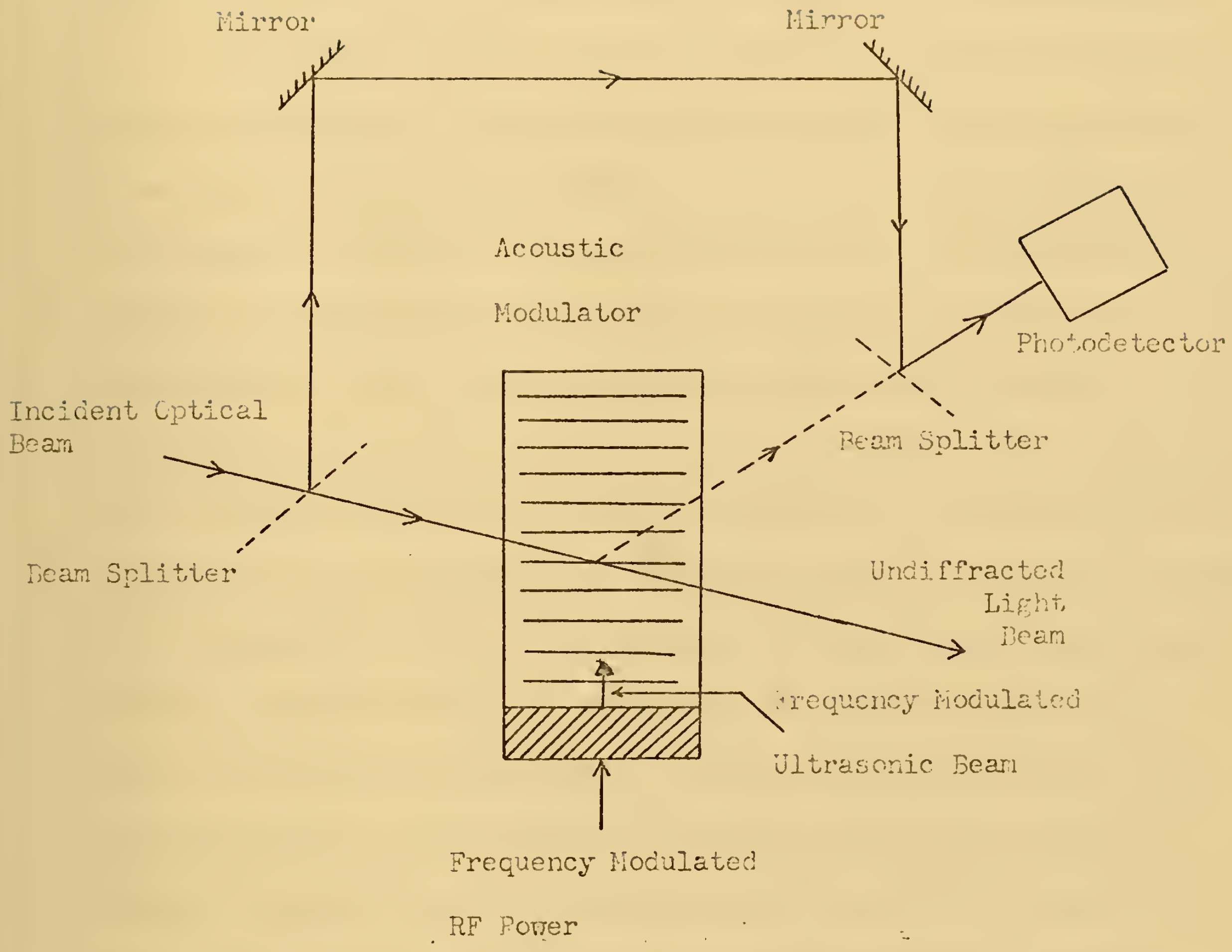


FIGURE 19 : MIRRORS AND BEAM SPLITTERS ARRENGEMENT FOR OPTICAL HETERODYNE DETECTION OF BRAGG DIFFRACTED LIGHT. (AFTER REF. 13)

the diffracted light. An optical detector placed in the path of this composite wave will detect the frequency-modulated diffracted light beams. The output of this optical detector will then be the frequency modulated electrical signal at rf frequencies, and the demodulation of this signal can be accomplished by a conventional FM radio or an FM discriminator.

Heterodyne detection process can also be accomplished using a laser local oscillator. The local oscillator and signal should be in phase across the whole photosurface of the detector. If they are not, beat currents at one part of the surface will be out of phase with beat currents at another part of the surface, resulting in signal loss. The optical mixing of the signal and local oscillator waves produces an intermediate-frequency (IF) signal carrying the laser carrier modulation. This IF signal is fed to an electrical detector or a conventional radio receiver for final demodulation. Frequency control of the local oscillator is necessary to correct for frequency drifting of the laser carrier and local oscillator and also compensate the possible large Doppler shift at the optical frequencies. For these purposes the laser local oscillator must be tunable over the necessary range. But there is generally a great amount of complexity and difficulty in tuning the laser local oscillator. Thus, frequency demodulation is currently impractical for long-range communications using this scheme.

4. Experiment

For this experiment the same light source and acoustic modulator were used as for the first experiment. A frequency modulated 5-MHz (fifth harmonic frequency of the X-Cut quartz-crystal transducer) rf sub-carrier signal was obtained from external frequency modulation of a high-frequency voltage-controlled oscillator (VCO) by an audio-frequency

oscillator. The transfer function of the high-frequency VCO is plotted in Fig. 20. From this figure it can be seen that the ratio of frequency deviation to the applied voltage is 2-MHz/volt. The bandwidth of the transducer was 0.05 MHz, therefore for the external frequency modulation of the high-frequency VCO, a 0.025 volt modulating sine wave signal was used. Driving power for the acoustic modulator was obtained from a wide-band power amplifier. Frequency modulation of the helium-neon laser beam by the frequency-modulated rf sub-carrier signal was achieved as described in Section II, (i.e. modulation of the acoustic wave frequency produced frequency modulation of the light beam). One of the frequency modulated diffracted beam (up-shifted) was selected from the acoustic modulator output and similar heterodyne detection set-up was used for detection of this diffracted beams as shown in Fig. 19. The HP-4220 PIN photodiode detector was used as a light detector. The detector pre-amplifier circuit was designed as shown in Fig. 21.

In the initial attempts demodulation was not achieved by the detector. The problem was at first believed to be the failure of the photodiode/pre-amplifier combination. Several alternative designs were attempted without success. Finally, measurement of the intensity of the diffracted beam showed that the portion of the diffracted beam power falling on the detector was too low. This problem was solved by putting the detector at the focal point of a converging lens, thus raising the light intensity on the detector.

Another problem in the frequency-modulated optical demodulation technique at rf frequencies was the presence of a spurious or leakage signal channel which appeared in addition to desired (optical) channel. This undesired signal was due to the radiation of rf power from the signal

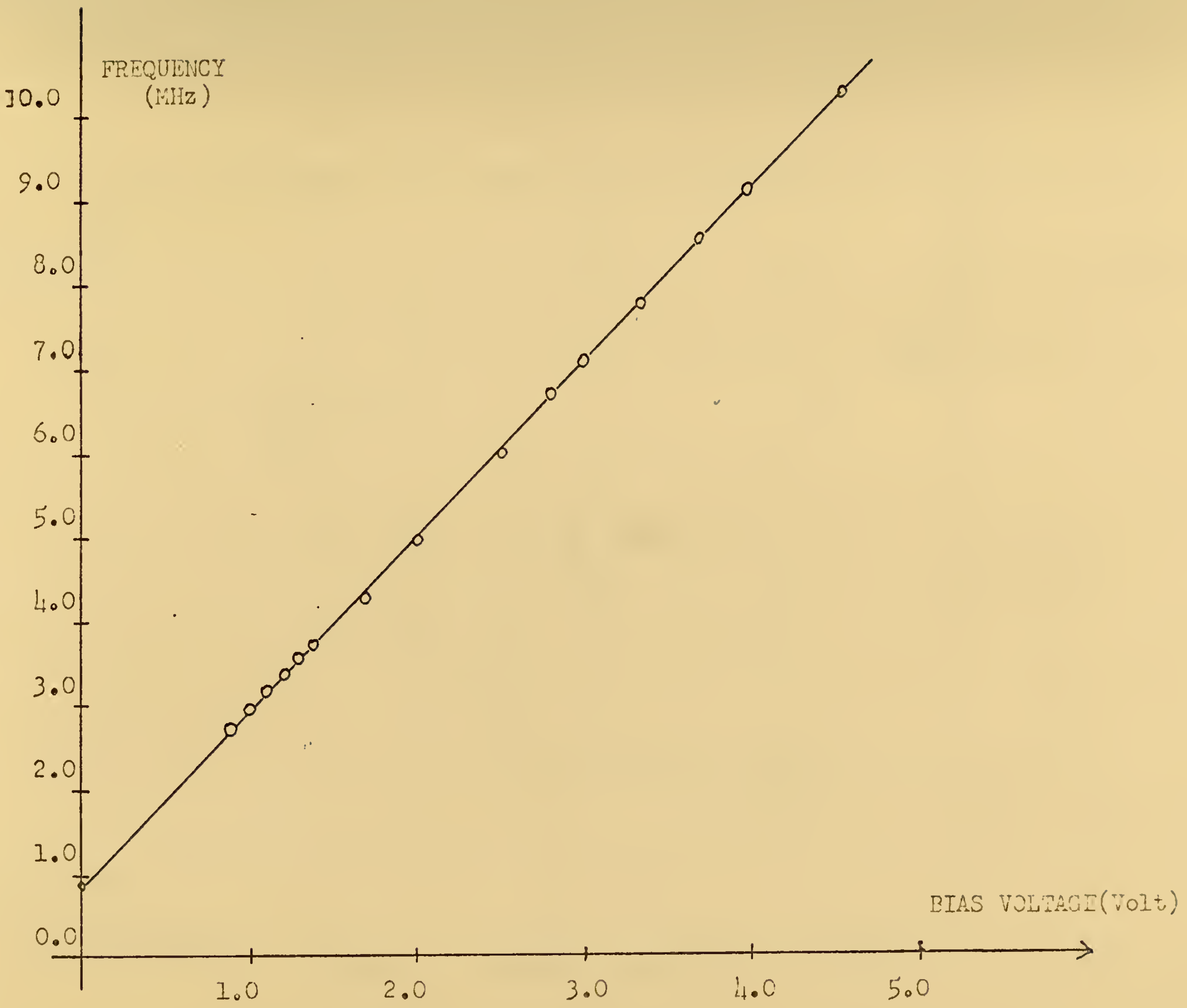
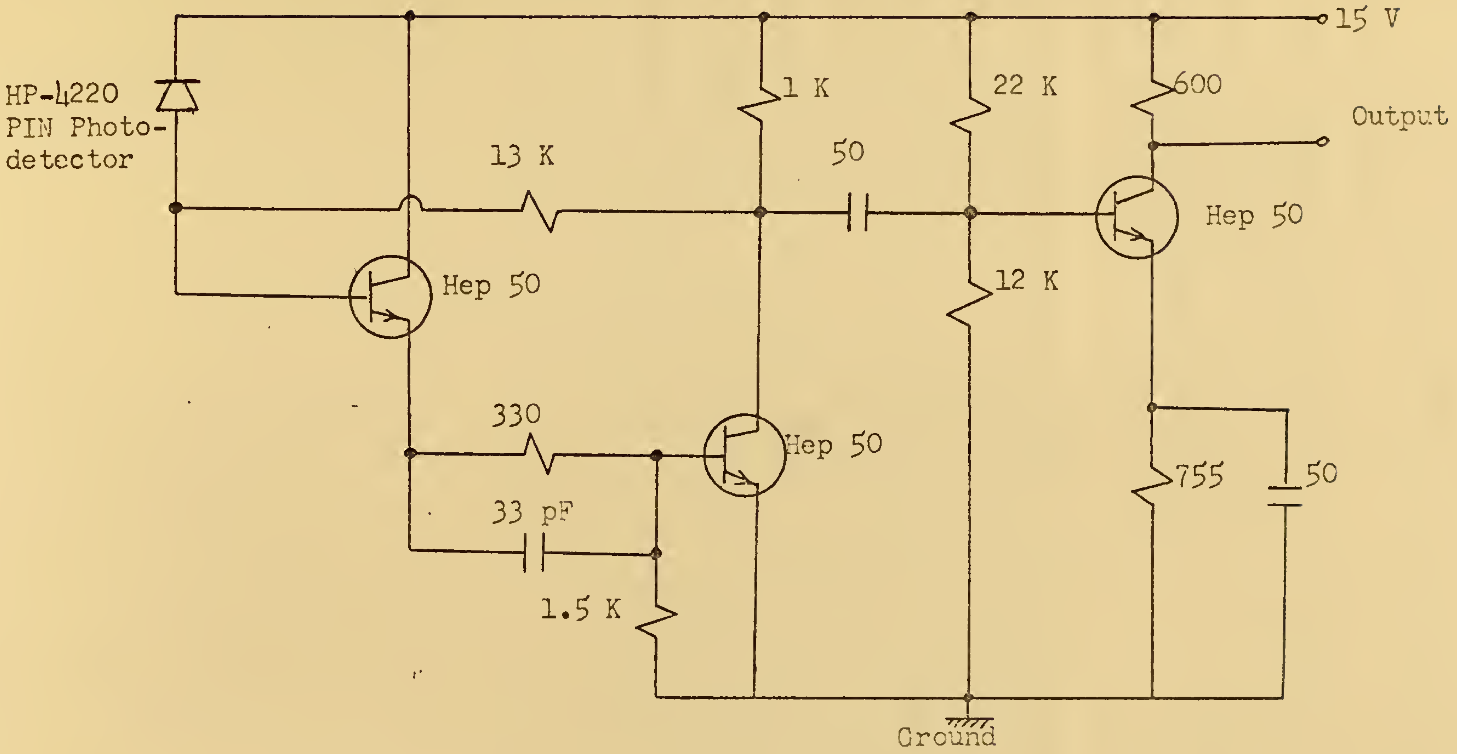


FIGURE 20 : VOLTAGE-CONTROLLED OSCILLATOR TRANSFER FUNCTION



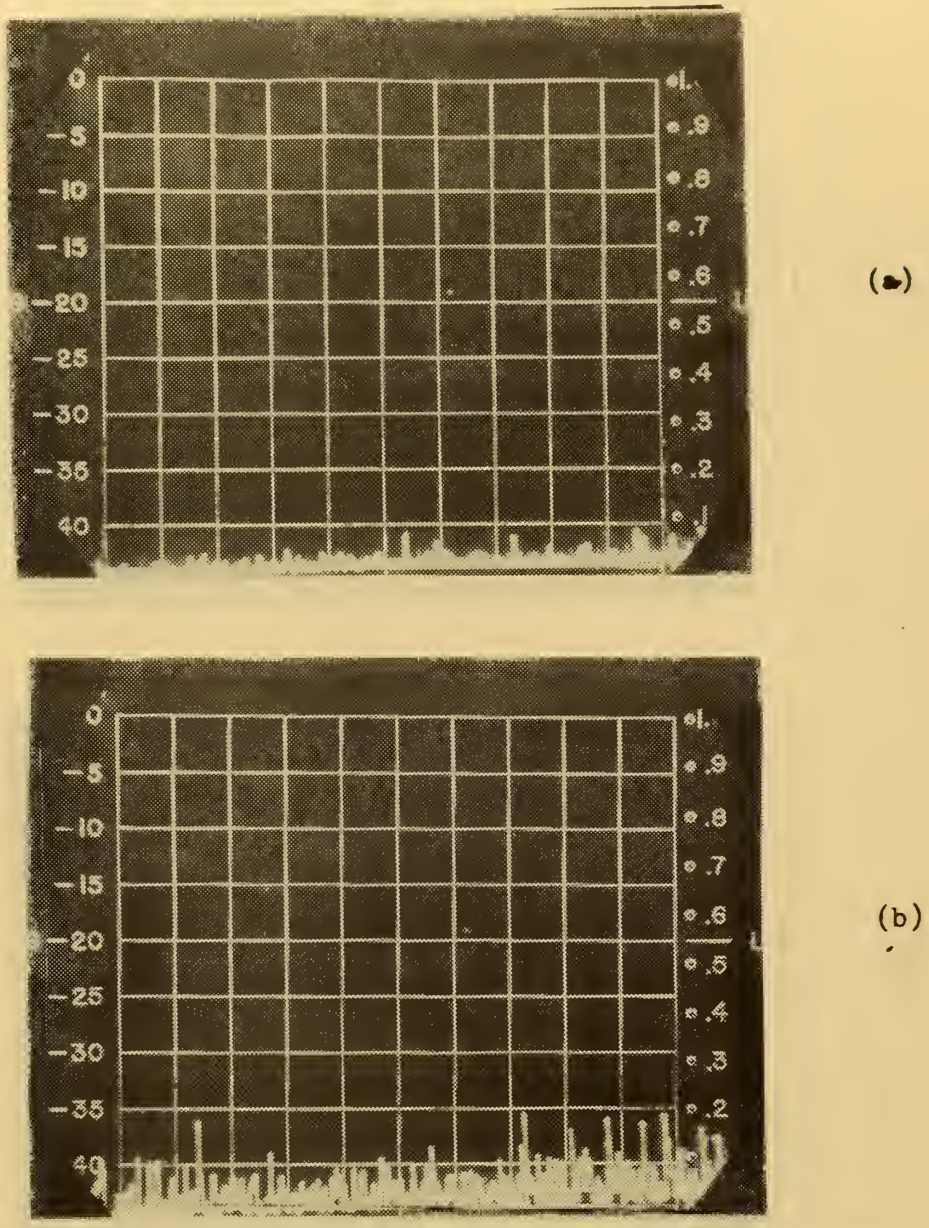
* R in Ohms

C in Microfarads

FIGURE 21 : DETECTOR PRE-AMPLIFIER CIRCUIT

generating and modulating systems ("leakage"), and the reception of that power in the receiving system ("pick-up"). This resulting rf leakage or interference signal in the receiving system was coherent with the desired rf signal since both originated from the same rf signal generators (VCO's) and acoustical modulator.

After reasonable precautions to avoid pickup the demodulated output from the photodiode detector was displayed and photographed on the spectrum analyzer as shown in Figures 22, 23, and 24. In these figures, the upper figure represents the noise and pickup (no signal present on the detector), and the lower figure represents the noise plus the signal on the detector. As seen from the difference of these upper and lower figures the signals are detectable. The output of the detector pre-amplifier was also fed into a radio receiver for final demodulation, and presented through head phones. The audio tone was audible although noise was also present. The comparatively large amount of noise present made an oscilloscope display of the signal impractical.



* Frequency Scale : f_{center} = 5 MHz, Bandwidth = ± 8 kHz

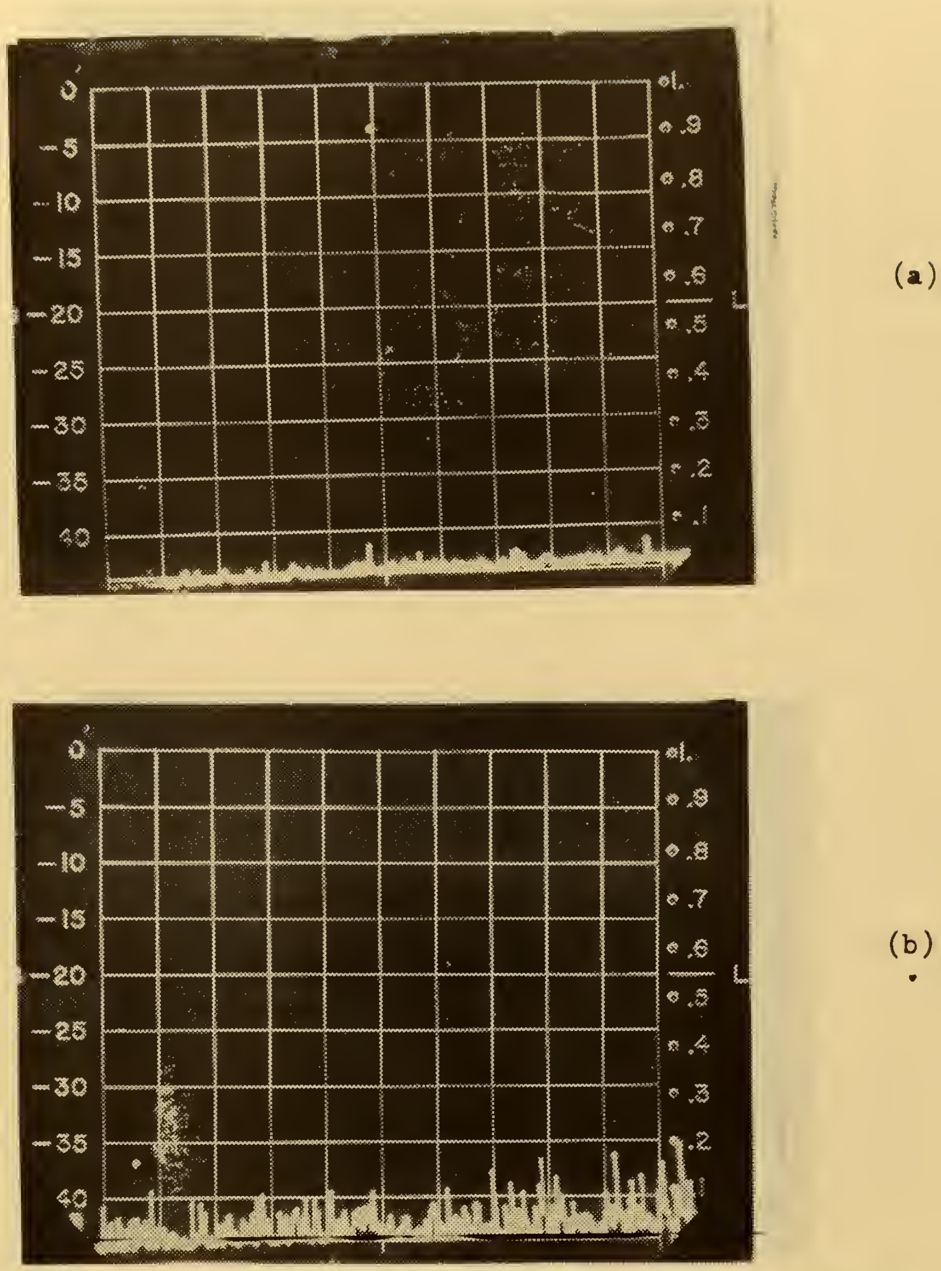
FIGURE 22 : THE PHOTODETECTOR OUTPUTS ON THE SPECTRUM ANALYZER

(a) No signal present on the photodetector (noise)

(b) 2-KHz modulating signal plus noise present

[illegible]

[illegible]



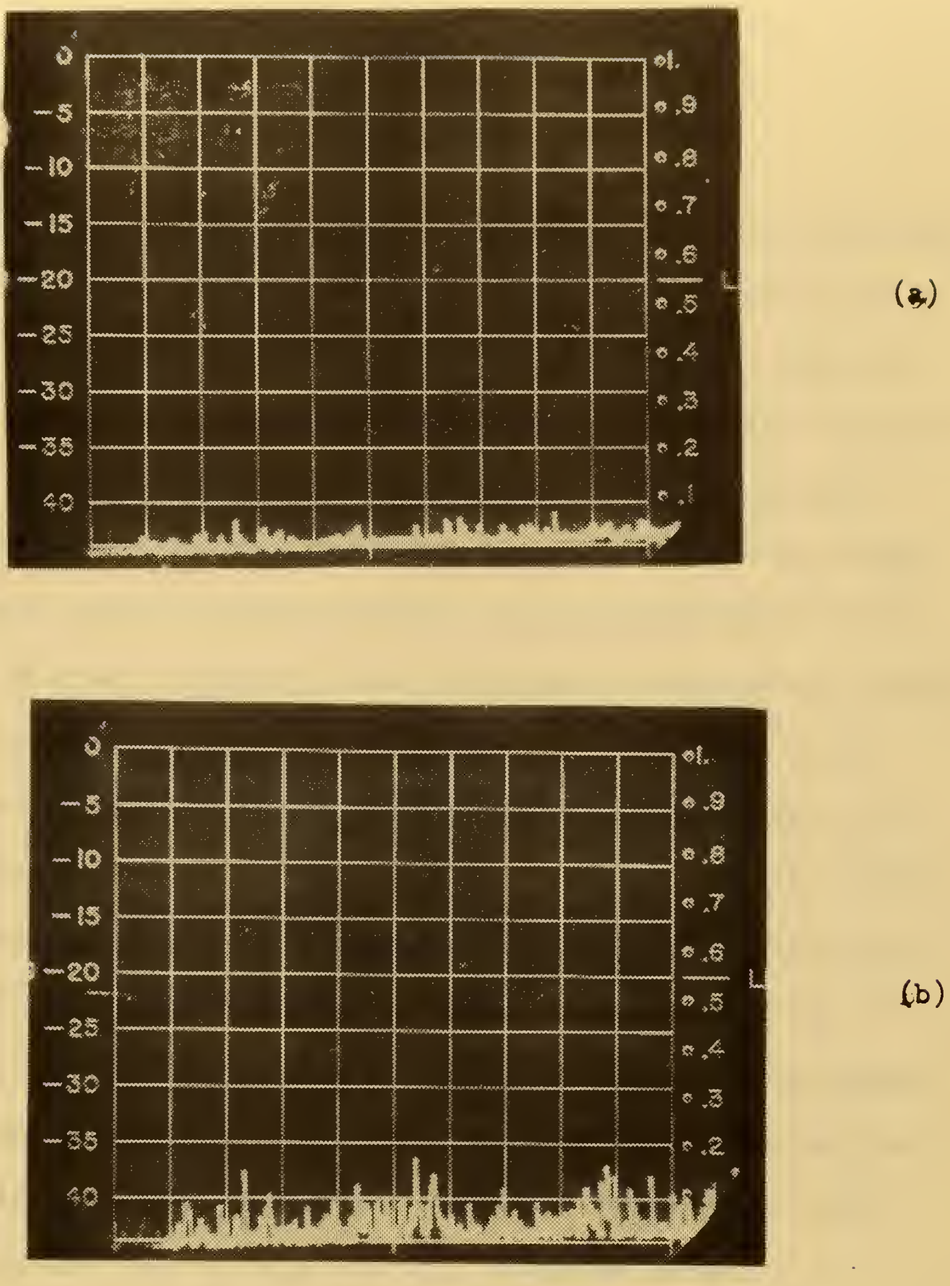
* Frequency Scale : f_{center} = 5 MHz, Bandwidth = ±8 kHz

FIGURE 23 : THE PHOTODETECTOR OUTPUTS ON THE SPECTRUM ANALYZER

(a) No signal present on the photodetector (noise)

(b) 5-KHz modulating signal plus noise present

[illegible]



* Frequency Scale : f_{center} = 5 MHz, Bandwidth = ± 8 kHz

FIGURE 24 : THE PHOTODETECTOR OUTPUTS ON THE SPECTRUM ANALYZER

(a) No signal present on the photodetector (noise)

(b) 20-KHz modulating signal plus noise present

[illegible]

IV. CONCLUSIONS

The amplitude modulated acoustical laser communication systems worked properly - the proposed designs were valid. The injection and subsequent reproduction of three test wave forms (sine, square, and triangular) was successful in the first communication tests. The injection of an audio signal as a modulating signal from a radio, proved marginally satisfactory - the wave form reproduced properly but the fidelity of the sound from the speaker was poor, but intelligible - in the second test. The poor fidelity can be attributed to the lack of filtering at the detector pre-amplifier stage, harmonic distortions due to the power amplifier (which was used before the acoustical modulator), and improper impedance matching between the audio amplifier and the speaker.

The frequency-modulated acoustical laser communication system also worked, but the radiation rf power from the signal-generating and modulating systems produced greater difficulty at the receiving systems. Because of these undesired signals, noise, and the increased sensitivity of the FM system to alignment, the quality of the demodulated output, although detectable, was not equal to that of the AM system.

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ABSTRACT

Acoustical amplitude and frequency modulation techniques of a CW helium-neon laser beam are presented. The communication possibilities of this beam for both cases (AM and FM) are verified. Theories are discussed for the acoustooptical modulator and the p-i-n silicon photodetector. Designs of the elements of the systems and experimental results are presented. Operation of both systems is discussed.

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